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Original article

Effect of minimal shoes and slope on vertical and leg stiffness during running

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Abstract

Purpose: This study was designed to characterize and compare the vertical (k_{vert}) and leg (k_{leg}) stiffness measured during running in two different footwear conditions on negative, level, and positive slopes, using kinematic data only.

Methods: Fourteen male recreational runners (age 23.4 ± 4.4 years, height 177.5 ± 5.2 cm, and body mass 69.5 ± 5.3 kg) were tested on 2 separate days within 1 week. At each session, subjects ran seven 5-min trials on a treadmill at 10 km/h, interspersed with 5 min of sitting passive recovery. Each trial was performed on a different slope gradient, ranging from -8% (downhill) to $+8\%$ (uphill), assigned in a random order. Furthermore, each subject ran one 5-min trial wearing minimal shoes (MS) and the subsequent trial wearing traditional shoes (TS) in a counter-balanced randomized order ensuring that each slope was ran once in MS and once in TS. Kinematic data were collected using a photocell measuring system and high-speed video camera, with k_{vert} and k_{leg} stiffness being calculated from these data.

Results: Leg compression, contact times, and vertical displacement of the center of mass during running were significantly smaller in MS compared to TS across all slopes. In the two footwear conditions, step frequency significantly increased with a (positive) increase in slope. Kinematic analyses indicated that k_{leg} was greater when running in MS than TS and this between-footwear difference remained similar across slopes. On the contrary, k_{vert} did not change on the basis of footwear, but increased with positive increases in slope.

Conclusion: This study showed that k_{vert} and k_{leg} during running respond differently to change in footwear and/or slope. These two stiffness measures can hence provide a unique insight on the biomechanical adaptations of running under varying conditions and their respective quantification may assist in furthering our understanding of training, performance, and/or injury in this sport.

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1. Introduction

The interest in barefoot and minimalist shoe (MS) running has exploded over the last decade with pretext that it is more natural than running in the modernized traditional shoe (TS). While offering more protection than barefoot, MS footwear

has a lighter mass, greater sole flexibility, lower profile, and smaller heel elevation compared to the TS.^{1,2} Given that the biomechanics of running in MS differ from TS to a smaller extent than those of barefoot running,^{1,3} the shift towards MS in runners is more widespread.

Similar to barefoot, MS running is 1%–3% more efficient than running in TS in terms of energy cost (Cr) on level,^{3–6} uphill and downhill terrain.⁶ Although shown to result mostly from the lighter shoe mass,^{4,5} this 1%–3% reduction in Cr has also been related to changes in running kinematics including decreases in contact times (t_c) and increases in step frequencies (f).^{3,5,6} Furthermore, several studies have reported

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higher leg stiffness (k_{leg}) during barefoot than TS running^{7–9} that, together with changes in running kinematics and foot strike patterns, may also contribute to lowering the Cr in barefoot or MS footwear compared to TS given that higher stiffness suggests greater ability to store and release elastic energy.¹⁰

Indeed, Kyröläinen and coworkers¹¹ have proposed that high muscle stiffness at the ankle and knee joints during the braking phase of running offers a suitable precondition for using the stretch-shortening cycle within muscle-tendon units, which enhances the mechanical efficiency, force potentiation and joint angular velocities and power during push-off at a negligible metabolic cost. While some authors have reported a lack of correlation between the leg stiffness and Cr values of runners,^{12,13} most evidence supports that increased k_{leg} is associated to better running economy,^{14,15} at least when running in TS or when comparing TS to barefoot running. Furthermore, the stretch-shortening cycle regulating stiffness does not only assist in decreasing the energetic cost of walking and running,¹⁶ but it also potentiates muscle actions¹⁷ and regulates the mechanical interactions between the body and the environment during the ground contact phase of locomotion.¹⁸

Although several articles provide insight on the relationship between running economy and lower extremity stiffness parameters – including muscle,¹⁵ tendon,¹⁹ leg,¹⁴ and vertical¹³ stiffness – these are moreover based on TS or barefoot than MS running. Even though MS approaches barefoot and offers a lightweight (~ 150 – 180 g per shoe) no motion control alternative to the TS,² the MS conventionally has a uniform sole thickness of ~ 1 cm that provides a small cushioning effect and shock absorption that are absent during barefoot. Although the sole is much thinner in MS than TS—which is about 2.5–3 cm at the heel and 1.5–2 cm at the forefoot—running in MS is not the same as barefoot and direct inferences of results from barefoot to MS are not fully substantiated. There is a paucity of papers reporting stiffness during running in MS, which would assist in furthering our understanding of training, performance, and injury in this sport.

In reality, a sufficient level of stiffness is required to optimize the utilization of the stretch-shortening cycle²⁰ and minimize the risk of musculoskeletal injury.²¹ More specifically, low leg stiffness has been associated to an increased risk of soft tissue injuries, whereas high leg stiffness to an increased risk of bone-related injuries.²² Although the appropriate amount of stiffness for runners has not yet been coined and is likely to vary on the basis of running discipline and individual characteristics,²³ quantifying stiffness under various running conditions in healthy individuals might assist in determining normative stiffness levels, understanding how the human body responds to changes in environmental conditions, and identifying maladaptive responses to training or pathological function. Such an understanding of human biomechanics is of interest to runners, coaches, and clinicians when preparing training, competition, injury prevention, and/or rehabilitation programs.

In this last context of uphill and downhill running, changes in slopes are frequent when running outdoors and clearly influence running biomechanics and physiology, including running velocity,²⁴ stride parameters,²⁵ the Cr ,⁶ and the stretch-shortening cycle.²⁷ For instance, increases in slope gradients have been associated to decreases in flight time (t_f) and elastic energy storage with increases in f and Cr .^{6,26} Although there are limits to the assessment of stiffness during slope running (e.g., the assumption of symmetric oscillations of the spring-mass model is not entirely respected), it seems important to investigate if and how stiffness changes with slope, and whether MS modulates these changes in stiffness. Such knowledge might be useful to runners in preventing injuries or promoting specific training adaptations, with individuals selecting situations that are associated with high and/or low stiffness values depending on which present the greatest benefits.

Whereas vertical stiffness (k_{vert}) is suggested to represent the overall body stiffness and defines the relationship between the ground reaction force and the vertical displacement of the center of mass, k_{leg} further represents the stiffness of the lower extremity complex (e.g., foot, ankle, knee, and hip joints) and describes the ratio between the ground reaction force and the deformation in leg length.²⁷ During locomotion, k_{vert} is always greater than k_{leg} because leg length changes exceed those of the center of mass.²⁷ Although k_{vert} and k_{leg} are derived from similar mechanical concepts, they are not synonymous and they adapt to changes in running conditions differently,^{8,28} which justifies examining both k_{vert} and k_{leg} .

Thus, the main objective of this study was to characterize and compare the k_{vert} and k_{leg} measured during running in MS to TS, using kinematic data only, with the hypothesis that stiffness would be greater in MS than TS in the level condition. A secondary objective was to investigate the effect of slope on these two stiffness measures, with the hypothesis that k_{vert} and k_{leg} would decrease during downhill and increase during uphill running, with stiffness always greater in MS than TS irrespective of slope.

2. Materials and methods

2.1. Subjects

Fourteen healthy male runners (mean \pm SD: age 23.4 ± 4.4 years, height 177.5 ± 5.2 cm, body mass 69.5 ± 5.3 kg, maximal aerobic velocity (MAV) 18.0 ± 1.4 km/h) participated in this study voluntarily. All subjects were recreationally trained runners running at least 45 km/week for the 6 months prior to this study. Most of the subjects were habituated to trail running, with 11 subjects reporting being trail exclusive runners ($\sim 100\%$ trail) and the remaining three being mixed runners ($\sim 70\%$ trail and $\sim 30\%$ road). No subject had previous experience in barefoot or MS running. All subjects were, and had been for the previous 12 months, free from injuries and able to run sub-maximally at 10 km/h on downhill, level, and uphill terrain. Each subject provided verbal and written informed consent before

participating in this study, which had been approved by the Franche-Comté university's Institutional Review Board.

2.2. Experimental protocol

The procedures employed here were similar to those described by Lussiana et al.⁶ and required each subject to report to a research laboratory on 2 separate days within 1 week for testing. The two sessions were conducted at the same time of day to limit diurnal variability, and the same experienced investigators administered the test sessions on both occasions to control for inter-tester variability. The ambient laboratory conditions were standardized to a temperature of $21.6 \pm 0.4 \text{ }^{\circ}\text{C}$ and hygrometry of $53.3\% \pm 1.2\%$. Subjects were familiarized with all test procedures and properly fitted in MS and TS on their first day to the laboratory. The MS footwear (Merrell Trail Glove; Merrell, Rockford, MI, USA) used in this study had a mass of $186.9 \pm 9.2 \text{ g}$ and drop of 0 mm, whereas the TS footwear (Salomon Speedcross 2; Salomon SAS, Annecy, France) had a mass of $333.4 \pm 13.9 \text{ g}$ and drop of $10.1 \pm 1.3 \text{ mm}$.

At the beginning of each data collection session, subject body mass was recorded barefoot. Subjects then performed a standardized $2 \times 5 \text{ min}$ warm-up running on a treadmill (Training Treadmill S1830; HEF Techmachine, Andrézieux-Bouthéon, France) at 10 km/h. Each 5-min block included running for 2 min at 0%, 2 min at +2%, and 1 min at -2%, where zero, positive, and negative slope values indicate level, uphill, and downhill running, respectively. The first 5-min block was completed in TS footwear and the second one in MS footwear.

Subsequently, at the two data collection sessions, subjects ran $7 \times 5 \text{ min}$ at 10 km/h using a self-selected step length and frequency, thus completing a total of $14 \times 5\text{-min}$ trials over a 1-week period. The $7 \times 5\text{-min}$ trials included one trial at each of the following slopes, in a randomized order: -8%, -5%, -2%, 0%, +2%, +5%, and +8%. Subjects had 5-min passive recovery, sitting on a chair, between each 5-min running trial. The first 5-min trial was started wearing either MS or TS, in a randomized order. After each 5-min trial, the footwear was changed during the recovery period to avoid habituation. For instance, if the first 5-min trial was in MS, the second one was in TS, the third in MS, and so forth until all $7 \times 5\text{-min}$ trials were completed. On the second data collection day for a given subject, the sequence of the seven slope conditions from the first test day was maintained, but the initial shoe condition was altered to ensure that each subject ran seven slopes in MS and seven slopes in TS during the week. A velocity of 10 km/h was selected for experimentation because it suited the aerobic capacity of our subjects and could be maintained in a steady state of oxygen-consumption at the steepest positive slope that was examined (i.e., +8%).

2.3. Measured parameters

The procedures used to collect and process running kinematics during the 5-min trials have been described in detail

elsewhere⁶ and are therefore only summarized here. An Optojump photocell system (Micro Gate; Timing and Sport, Bolzano, Italy) sampling at 1000 Hz was placed adjacent to the treadmill. The Optojump recorded contact times and flight times over 30 s, in continuous, from minute 2 to 2.5 and from minute 4 to 4.5 of each 5-min running trial. For joint angle computations, a high-speed digital video camera (Sony HDR-SR7E; Sony Corporation, Tokyo, Japan) sampling at 200 Hz was positioned 2 m from and perpendicular to the acquisition space on a 45-cm tripod. The video camera was used to track markers that were placed over the right trochanter, lateral femoral condyle, lateral malleolus, tuber calcanei, and fifth metatarsal phalangeal joint. Plantar-foot, ankle, and knee joint angles were computed using standard off-line digitization procedures^{6,7} in the Dartfish Pro Analysis Software v.5.5 (Dartfish company, Fribourg, Switzerland). Data from the two 30-s epochs of each trial were averaged and used in further data processing.

2.4. Calculated parameters

As described by Morin et al.,²⁹ the spring-mass characteristics were estimated using a sine-wave model employing t_c , t_f , f , velocity (v), body mass (m), and leg length (L , the distance between the greater trochanter and the ground measured in barefoot upright stance). The sine-wave model approach was selected because, in absence of synchronous and direct kinetic and kinematic measures, this model provides the most reasonable estimate of stiffness during running in comparison to other mathematical models.³⁰

It is to note that the spring-mass model assumes a symmetric oscillation of the system during ground contact,²⁷ which is not entirely respected during slope running. For this reason, the comparison between stiffness values should be made at 0% first, and interpreted with some caution when comparing values on positive or negative slope gradients. Nonetheless, the different slope gradients analyzed here remain light when compared to others³¹ and induce relatively small biomechanical changes that violate the symmetric oscillation assumption of the spring-mass model. Thus, the compromise between the requirements of the model and the current experimental sloped conditions appeared reasonable.

Vertical stiffness (k_{vert} , kN/m) was calculated as the ratio between the maximal vertical force (F_{max} , kN) and center of mass displacement (Δy , m):

$$k_{\text{vert}} = F_{\text{max}} \times \Delta y^{-1} \quad (1)$$

with:

$$F_{\text{max}} = mg \times \left(\frac{\pi}{2}\right) \times \left[\left(\frac{t_f}{t_c}\right) + 1\right] \quad (2)$$

and:

$$\Delta y = \left| -\frac{F_{\max}}{m} \times \frac{t_c^2}{\pi^2} + g \times \frac{t_c^2}{8} \right| \quad (3)$$

Leg stiffness (k_{leg} , kN/m) was calculated as the ratio between the F_{\max} and maximal leg length deformation, i.e., leg spring compression (ΔL , m):

$$k_{\text{leg}} = F_{\max} \times \Delta L^{-1} \quad (4)$$

with:

$$\Delta L = L - \sqrt{L^2 - \left(\frac{vt_c}{2}\right)^2} + \Delta y \quad (5)$$

2.5. Statistics

Data were described using mean \pm SD values. All data were normally distributed on the basis of Kolmogorov–Smirnov tests. Parametric statistical methods were therefore employed to analyze data, which included two-way (footwear \times slope) repeated measures analyses of variance (RM ANOVA) and Holm–Sidak procedures during *post-hoc* pair-wise comparisons. Statistical significance was accepted at $p < 0.05$. All analyses were performed using SigmaStat for Windows 3.5 (Systat Software Inc., San Jose, CA, USA).

3. Results

3.1. Spring-mass characteristics

The mean \pm SD values for k_{vert} and k_{leg} for the different running conditions are illustrated in Fig. 1. The two-way RM ANOVA indicated no significant interaction effects from footwear and slope on k_{leg} ($p = 0.543$) and k_{vert} ($p = 0.861$). The main effects of footwear on k_{leg} ($p < 0.001$) and of footwear ($p = 0.021$) and slope ($p < 0.001$) on k_{vert} were significant, but there was no main effect of slope on k_{leg} ($p = 0.543$).

On level (i.e., 0%), k_{leg} was significantly greater in MS compared to TS ($p < 0.001$) whereas k_{vert} showed similar values ($p = 0.227$). These between-footwear patterns in k_{leg} and k_{vert} were maintained in uphill and downhill conditions, except at -5% and $+8\%$ where k_{vert} was greater in MS compared to TS. Regardless of footwear, k_{vert} was greater when running at more positive gradients ($p < 0.001$), while k_{leg} remained similar ($p = 0.543$).

3.2. Kinematics

The mean \pm SD values for t_c , t_f , and f are provided in Table 1 and for Δy , ΔL , and F_{\max} in Table 2. The two-way

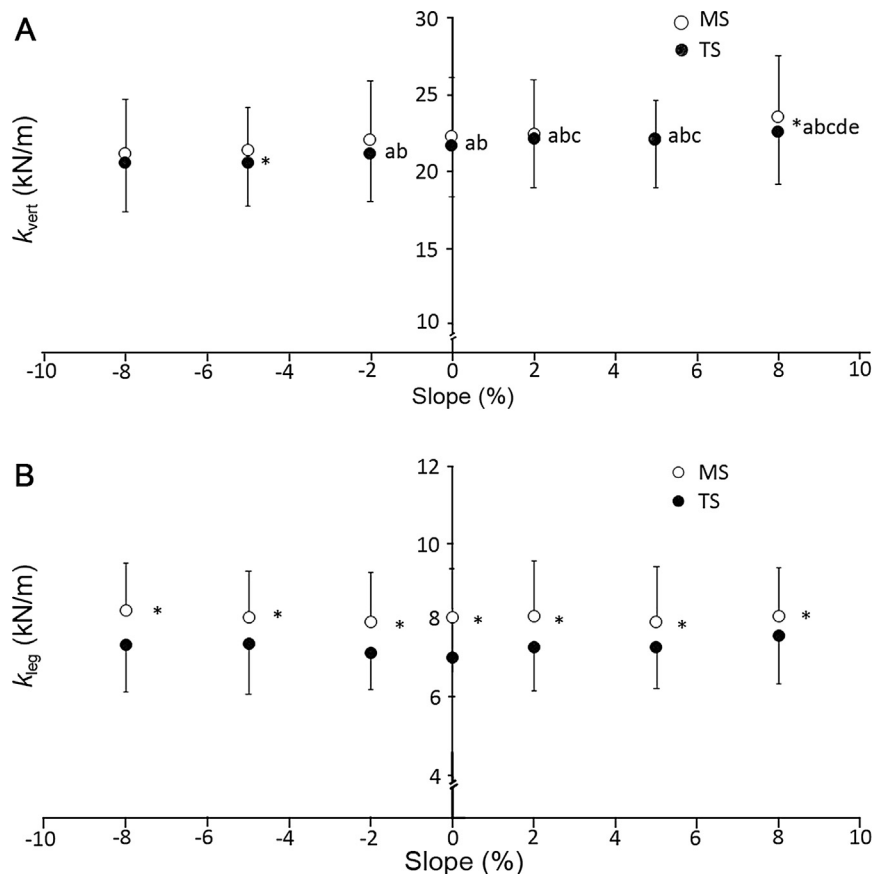


Fig. 1. Vertical (k_{vert} , A) and leg (k_{leg} , B) stiffness in traditional (TS) and minimal (MS) shoes on different slope gradients. Level of significance is $p < 0.05$. Letters (a, b, c, d, e) indicate a significant difference between slope conditions compared to -8% , -5% , -2% , 0% , $+2\%$, respectively. * indicates a significant difference between shoe conditions, $p < 0.05$.

Table 1

Contact time (t_c), flight time (t_f), and step frequency (f) during running in traditional (TS) and minimal (MS) shoes on different slope inclines (mean \pm SD).

Slope (%)	t_c (ms)			t_f (ms)			f (step/s)		
	MS	TS	MS vs. TS	MS	TS	MS vs. TS	MS	TS	MS vs. TS
-8	290 \pm 14	308 \pm 20	*	87 \pm 27	71 \pm 30	*	2.67 \pm 0.17	2.65 \pm 0.14	—
-5	293 \pm 16	307 \pm 20	*	78 \pm 22	71 \pm 26	—	2.70 \pm 0.10	2.66 \pm 0.12	*a
-2	295 \pm 18	309 \pm 19	*	71 \pm 27	63 \pm 27	a	2.70 \pm 0.17	2.70 \pm 0.09	ab
0	294 \pm 18	313 \pm 19	*	71 \pm 28	55 \pm 28	*ab	2.75 \pm 0.16	2.72 \pm 0.10	ab
2	293 \pm 18	308 \pm 18	*	70 \pm 27	55 \pm 23	*ab	2.76 \pm 0.14	2.76 \pm 0.09	ab
5	295 \pm 18	308 \pm 20	*	66 \pm 19	56 \pm 27	ab	2.77 \pm 0.10	2.75 \pm 0.11	*abc
8	293 \pm 18	301 \pm 19	*	61 \pm 25	59 \pm 26	ab	2.83 \pm 0.12	2.77 \pm 0.11	*abc
Shoes main effect	$p < 0.001$			$p = 0.010$			$p = 0.016$		

Note: Level of significance is $p < 0.05$.

Letters (a, b, c) indicate a significant difference between slope conditions compared to -8%, -5%, -2%, respectively.

* indicates a significant difference between shoe conditions.

RM ANOVA indicated no significant interaction effects from footwear and slope on all parameters ($p \geq 0.178$). However, there was a significant main effect of footwear and slope on all these kinematic parameters (all $p \leq 0.016$) with the exception of footwear on Δy ($p = 0.410$) and slope on t_c ($p = 0.567$).

In general, lower t_c , higher t_f , and f values were recorded when running in MS compared to TS in all seven slope conditions, but not all *post-hoc* pair-wise comparisons reached statistical significance (Table 1). For instance, on level, t_c ($p < 0.001$) was smaller and t_f ($p = 0.014$) was greater in MS than TS footwear, but f showed similar values ($p = 0.335$). At $\pm 5\%$, only t_c and f differed significantly between MS and TS, where t_c was lower and f was higher in MS.

Similarly, running in MS versus TS generally provided lower ΔL and higher F_{\max} values. F_{\max} significantly differed between footwear conditions at -8%, 0%, and +2% only (Table 2).

Overall, a positive increase in slope gradient was associated with an increase in f and a decrease in t_f , Δy , and F_{\max} (Tables 1 and 2). The ΔL did not vary significantly when comparing two different slope gradients, except when comparisons were made to +8% where ΔL was the lowest. The extent of the difference between the kinematic values was always greatest when the two extreme slope conditions were compared (i.e., -8% vs. +8%).

4. Discussion

In accordance with our primary hypothesis, leg stiffness (k_{leg}) during level running was greater in MS than TS. However, there were no differences between footwear with respect to vertical stiffness (k_{vert}). The disparity in k_{leg} between footwear remained similar at the different slope gradients investigated here, thus agreeing with our secondary hypothesis. In addition, our results showed an impact of the slope gradient on k_{vert} (i.e., k_{vert} increased with a positive increase in the slope), despite the lack of change in k_{leg} with slope.

Similar to experiments involving barefoot running,⁷⁻⁹ k_{leg} was greater in MS than TS. These findings are consistent with the inverse relationship reported by Aerts and De Clercq³² between heel-pad compression and midsole hardness determined from a series of pendulum impact tests at the heel. These authors showed that heel-pad stiffness increased with the rate of loading, which was coupled with the amount of midsole hardness. Their results demonstrate, in theory, foot adaptations to footwear that assist in explaining the increase in k_{leg} values observed herein in MS versus TS footwear. Various other arguments can be advanced to explain the observed differences in k_{leg} between footwear, which are addressed below.

In the current research, our subjects demonstrated a significant decrease in ΔL and increase in F_{\max} when running in

Table 2

Downward displacement of the center of mass (Δy), leg compression (ΔL), and maximal vertical force (F_{\max}) in traditional (TS) and minimal (MS) shoes on different slope inclines (mean \pm SD).

Slope (%)	Δy (cm)			ΔL (cm)			F_{\max} (kN)		
	MS	TS	MS vs. TS	MS	TS	MS vs. TS	MS	TS	MS vs. TS
-8	6.7 \pm 1.0	6.5 \pm 1.0	—	17.0 \pm 1.4	18.2 \pm 1.5	*	1.39 \pm 0.14	1.32 \pm 0.15	*
-5	6.4 \pm 0.7	6.5 \pm 0.8	—	16.5 \pm 1.3	18.1 \pm 1.7	*	1.36 \pm 0.13	1.32 \pm 0.14	—
-2	6.1 \pm 1.0	6.1 \pm 0.9	ab	17.0 \pm 1.7	17.7 \pm 1.5	*	1.32 \pm 0.14	1.29 \pm 0.12	a
0	6.1 \pm 1.0	5.9 \pm 0.9	ab	16.7 \pm 1.5	17.7 \pm 1.2	*	1.33 \pm 0.14	1.27 \pm 0.12	*ab
2	6.0 \pm 0.9	5.8 \pm 0.7	ab	16.6 \pm 1.4	17.5 \pm 1.2	*	1.33 \pm 0.15	1.27 \pm 0.12	*ab
5	5.8 \pm 0.9	5.8 \pm 0.9	abcd	16.6 \pm 1.5	17.5 \pm 1.2	*	1.30 \pm 0.13	1.27 \pm 0.12	ab
8	5.6 \pm 0.8	5.7 \pm 0.8	abcde	16.1 \pm 1.2	16.9 \pm 1.2	*abcd	1.29 \pm 0.11	1.28 \pm 0.12	ab
Shoes main effect	$p = 0.410$			$p < 0.001$			$p = 0.006$		

Note: Level of significance is $p < 0.05$.

Letters (a, b, c, d, e) indicate a significant difference between slope conditions compared to -8%, -5%, -2%, 0%, +2%, respectively.

* indicates a significant difference between shoe conditions.

MS on level compared to TS, which necessarily resulted in higher k_{leg} conforming to equation (4). This decrease in ΔL could be caused by the reduced time during which the foot was in contact with the ground and received ground reaction forces; as suggests the lower t_c and, indirectly, higher f observed in MS (Tables 1 and 2). In fact, decreases in t_c and increases in f have been associated with increases in k_{leg} previously,^{33,34} with the change in t_c suggested to explain up to 90% of the change in k_{leg} .³⁴

Regarding the effect of footwear on F_{max} during running, there is conflicting evidence with studies reporting no differences between TS, MS, and barefoot conditions;^{3,5,7} lower impact forces in barefoot and MS than TS;³⁵ and, comparable to our findings, higher F_{max} in barefoot and MS than TS.³⁶ Two plausible explanations for these variable findings are the between-study differences in the methods employed to collect and compute F_{max} and the degree of habituation of runners to the experimental footwear conditions. In our study, t_c and t_f were decisive parameters in the estimation of F_{max} (c.f., equation (2)), with the significantly greater t_f in MS compared to TS at -8% , 0% , and $+2\%$ explaining the significantly greater F_{max} in MS at these slope gradients. These heightened F_{max} are of concern taking into account that high impact forces are proposed to increase the risk of overuse and/or impact related running injuries.³⁷ This is of particular relevance to runners transitioning from TS to MS considering that foot bone marrow edema (a swelling/inflammation of the bone marrow with excess fluid in reaction to stress) can increase significantly during this time due to added stress, which might ultimately result in stress fractures with improper conditioning and/or habituation.³⁸ Furthermore, our subjects had no previous barefoot or MS running experience, which contrasts to most of the studies showing findings in contradiction to ours. In all probability, lower F_{max} values would have been found here if our subjects had been trained or experienced in running barefoot or in MS.^{39,40}

Kinematic data associated to the same experimental protocol than the one examined here⁶ have shown greater plantar-foot (at all slope gradients) and plantar-flexion (except at $+5\%$ and $+8\%$) angles at foot contact in MS than TS, suggesting a more frequent midfoot and/or forefoot than rearfoot strike pattern in minimalist footwear. Such biomechanical adaptations to change in footwear from TS to barefoot have been reported previously together with greater k_{leg} during barefoot running.⁷ Increases in k_{leg} during running are proposed to result from decreases in the angles swept by the leg during stance³³ and, together with foot strike patterns, can provide potential explanations to the differences in k_{leg} between TS and MS footwear herein. In fact, a recent investigation has shown that increases in plantar-foot and plantar-flexion angles during ground contact cause significant changes in the spring-mass characteristics describing human motion, with higher k_{leg} and k_{vert} values.⁴¹

The differences in k_{leg} between MS and TS that we report here might also arise from differences in tactile sensitivity between footwear. Squadrone and Gallozzi⁴² observed that ankle joint position sense was enhanced when wearing MS compared to TS and that individuals were able to estimate

slope gradients with better accuracy when running in MS. A better estimation of slope gradient may permit runners to modulate muscle activation and/or joint kinematics in a way that increases stiffness and potentiates the use of the stretch-shortening cycle to enhance performance. On the contrary, Squadrone and Gallozzi⁴² found that wearing TS decreased ankle joint position sense, with evidence from other researchers that reducing plantar tactile sensitivity through lidocaine injection at the ankle decreases k_{leg} during hopping,⁴³ supporting our findings of lower k_{leg} in TS than MS. Moreover, increasing plantar sensory input has been shown to cause an increase in midfoot plantar pressure;⁴⁴ which, assuming greater sensory input in MS, agrees with the greater F_{max} that we observed here in MS footwear.

On the other hand, no difference in k_{vert} between MS and TS was observed in our runners. These results are consistent with those from Shih et al.⁹ where no differences in k_{vert} between TS and barefoot running conditions were identified. In this study by Shih et al., all subjects were habitual rearfoot strikers and instructed to use either their habitual rearfoot or a novel forefoot strike pattern. Strike patterns did not influence k_{vert} or the vertical displacement of the center of mass, despite causing changes in lower extremity loading rates and angular kinematics. When adapting to a new running surface, runners can adjust leg stiffness to maintain their vertical displacement of the center of mass, thereby permitting a smooth transition between surfaces.⁴⁵ It is likely that runners habituated to rearfoot striking and/or TS footwear adapt to new foot strike patterns and/or footwear in a similar manner, explaining the lack of change in k_{vert} with foot strike pattern and/or footwear, as found here.

On the contrary, Divert et al.⁸ reported increases in k_{vert} during running barefoot compared to shod. These authors suggested that the increase in k_{leg} during barefoot running was not sufficient to maintain k_{vert} constant,⁸ as opposed to when running on a new surface where adjustments are proposed sufficient.⁴⁵ In our study, Δy was not influenced by footwear despite a decrease in t_c and an increase in f observed in MS. We can suppose that wearing MS did not induce enough changes in the k_{leg} of our runners to cause a marked increase in k_{vert} , which might have been different if tested barefoot.

A second purpose of our study was to describe the effects of slope on k_{leg} and k_{vert} . We have recently reported a decrease in Cr when wearing MS compared to TS that was independent of slope gradients ranging from -8% to $+8\%$.⁶ Thus, we assumed a constant difference in stiffness between MS and TS regardless of slope, which was confirmed for k_{leg} . As noted above, the symmetric oscillation assumption of the spring-mass model is not fully respected during slope running, like during sprint accelerations or running on a curve.^{46,47} This implies a certain limit to studying stiffness on slopes and our results should be viewed with some caution. However, it is important to investigate situations habitually encountered by runners, with the investigation conducted here complementing the described changes in Cr and kinematics with slope and footwear.

When running downhill, we found that k_{vert} remained constant compared to level, but became greater when running

uphill. In our prior investigations, we found greater knee flexion angles during downhill compared to uphill running.⁶ This biomechanical adaptation is reported to provide a mechanical cushioning that attenuates the impact forces at ground contact,⁴⁸ which are considerably higher during downhill compared to flat and/or uphill running.⁴⁹ An increase in knee flexion during ground contact also increases the vertical displacement of the center of mass and thereby causes the k_{vert} to decrease.²⁸ Moreover, our previous kinematic data suggest a greater use of midfoot and/or forefoot strike patterns than rearfoot during positive compared to negative slope running.⁶ The rearfoot strike pattern is reported to induce a higher t_c ⁷ that can also cause an increase in the vertical displacement of the center of mass⁵⁰ and contribute to decreasing k_{vert} during downhill running. Other studies have shown that increases in f with decreases in Δy during level running cause increases in k_{vert} .^{33,34} In agreement with these findings and other running reports, we observed an increase in f compared to level when slopes were positively increased²⁵ with a maintenance in f when running downhill.²⁶ At the same time, as slopes were positively increased, we found a reduction in Δy with a simultaneous decrease in F_{max} that would stabilize k_{vert} values on the basis of equation (1). However, because F_{max} varied to a smaller extent than Δy as slopes became more positive (i.e., 5.2% and 14.4% from -8% to $+8\%$, respectively), k_{vert} became greater.

In contrast, k_{leg} remained constant across the seven slope conditions under investigation. At low slope gradients (i.e., $\pm 2\%$ in Table 2), neither ΔL nor F_{max} varied substantially and could therefore alter k_{leg} . However, at more pronounced slopes, F_{max} was lower when running uphill than downhill with ΔL being much lower at $+8\%$ compared to level and all downhill conditions. On the basis of equation (4), these changes could have caused significant decreases in k_{leg} during uphill running, but these were too small and thus k_{leg} remained stable across all slopes. Significant differences in k_{leg} would probably appear at more extreme slope gradients.

In parallel, in reference to equation (2), t_f and t_c provide information on F_{max} . The proportion of time spent on the ground (t_c vs. t_f) during each step was greater as slopes became increasingly positive. It is thus logical that we observed a slight decrease in F_{max} when the slope was increased contrary to findings derived from kinetic measurements.⁴⁹ The significantly lower ΔL at $+8\%$ can be explained by the considerably higher step frequency selected by our runners at this gradient. When slopes become positive, f increases²⁵ and the angles swept by the lower extremity from the initial contact to mid-stance decrease,³³ concurring with the decrease in ΔL observed at $+8\%$.

The stiffness values during running obtained from our experiment are somewhat lower than others previously reported;⁵¹ but in the latter research, higher running velocities were employed which often leads to higher stiffness values.⁵² In our study, we selected a 10 km/h velocity on the basis of our subjects' aerobic capacities and the sloped experimental protocol. It is not clear how our results would differ at faster and/or slower running velocities, which could be examined in future investigations. Computational methods also affect stiffness

values²⁹ with the method used here reported to underestimate actual stiffness by up to 7% when compared to kinetic-based computations.²⁹ We are nonetheless confident that our kinematic results provide a contextually accurate estimate of the actual stiffness considering that the indirect method that we used for evaluating stiffness has been deemed superior to others.³⁰ Moreover, within the context of our study, the systematic bias in computations would remain in all conditions (i.e., footwear \times slope) and comparisons made, which should therefore not influence the overall interpretations of findings. Finally, different shoe models can influence research results and their interpretation. For instance, some investigations report no major differences in running kinematics between MS and TS^{1,53} that likely result from footwear models employed, with some MS models like the Nike Free 3.0 offering a certain cushioning and heel elevation. The MS model that we employed (Merrell Trail Glove) has a thin flexible rubber sole that offers low cushioning and no heel elevation, resembling the Vibram Five-Finger that has been used in other investigations that report findings comparable to ours.^{3,42}

5. Conclusion

This study provides evidence that wearing MS increases k_{leg} during level treadmill slope running in comparison to TS, without influencing k_{vert} , which remains similar when running uphill and downhill. A second observation was that k_{vert} increased with a positive increase in slope gradient, whereas k_{leg} did not. Overall, these findings indicate that k_{vert} and k_{leg} during running respond differently to change in footwear and/or slope. Consequently, these two stiffness measures can provide a unique insight on the biomechanical adaptations of running under varying conditions and their respective quantification may assist in furthering our understanding of training, performance, and/or injury in this sport. With this knowledge, runners, coaches, and clinicians may select a combination of running conditions that increase and/or decrease k_{vert} and/or k_{leg} on the basis of training and/or rehabilitation goals.

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